Tilt-corrected stitching for electron beam lithography

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Abstract

This paper demonstrates significant improvements in the stitching performance of an electron beam lithography tool by correcting for wafer tilt. This is achieved with no significant increase in writing time. Wafer tilt gives rise to keystone errors in the writing field and even for modest tilts the stitching error can increase significantly. By applying suitable corrections to the main field the maximum stitching error was reduced from 34 to 12 nm for a wafer tilt of 2 mrad.

Keywords: electron-beam lithography, stitching, tilt
1. Introduction

Stitching errors in electron beam lithography occur when adjacent writing fields do not match up exactly. For many applications these errors can cause a serious loss in performance and there is a considerable body of work showing how the effects of stitching can be minimised. The main methods are to superimpose multiple exposures using different field sizes [1, 2], reduce the field size [3], and to eliminate fields altogether by using a continuous MEBES type writing strategy[4]. Both of the first two methods increase writing times whereas the continuous writing strategy only improves stitching in one dimension.

Dougherty et al [2] mention wafer tilt as a cause of stitching error. Typically electron beam tools correct for gain and rotation errors which are induced by variations in the wafer height, which is measured as a change in distance from the final lens to the wafer surface. Wafer tilt gives rise to variations in the wafer height across a writing field and this is not usually corrected for. There is a trend for electron beam tools to have larger fields and better stitch performance, and both these exacerbate the problem of wafer tilt. The Vistec VB6 UHR EWF electron beam lithography tool has a maximum stitch error of around 15 nm, a field size of 1.2 mm and can write 10 nm lines across this field. This stitching performance is obtained relatively easily on a mask plate which can be kept level to a tilt of better than 0.2 mrad. But when writing on a plate tilted at 0.4 mrad the maximum stitch error increased to 38 nm, and values of tilt bigger than this are not uncommon on wafers which are often bowed because of process-induced stresses.

This paper investigates the stitching errors arising from substrate tilt in electron beam lithography and shows that tilt induces keystone distortion in the main field. These errors can be reduced by applying suitable corrections to the main field without suffering the penalty of increased writing time.

2. Modelling the effect of tilt

Fig 1 (a) shows schematically a tilted wafer and the electron trajectories from the final scan pivot point, O, as seen from the side. The wafer lies along PT whereas the ideal untilted wafer plane is PS. The angle of tilt is α. Fig. 1 (b) shows the same situation, but viewed from above. Four electron trajectories are shown, each landing at one of the four corners of a square field centred at O. On the left hand side of the field the electron trajectories meet the tilted wafer plane closer to O than they should, whereas to the right they meet the wafer further from O. As a result the square field becomes a trapezium on the tilted wafer, as shown. When these fields are stitched together there will be y keystone stitch errors which are maximum at the corners and zero at the centre of each edge. The shift of the corner from S to T also causes a distortion in the x direction. But this does not lead to stitching errors since it has the same sense on both sides of the field.
In a similar manner, a tilt in the $y$ direction leads to $x$ keystone errors; and for a combination of $x$ and $y$ tilt the $y$ and $x$ errors are simply added.

In reality the situation is more complex since the final pivot point is within the final lens and the electrons spiral about the $z$ axis as they pass through the lens. This is shown schematically in Fig 1(c) and (d). The result is a rotation in the keystone error so that a tilt in the $y$ direction leads to both $x$ and $y$ keystone error.

The distortions ($\Delta x, \Delta y$) at the point $(x, y)$ caused by a tilts $(t_x, t_y)$ in $x$ and $y$ can be calculated using coordinate geometry. Neglecting second order terms in the tilts the distortions are given by:

$$ \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = \frac{\kappa}{L} \begin{bmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{bmatrix} \begin{bmatrix} x & y \\ t_y - x^2 t_x & \end{bmatrix} \begin{bmatrix} -x & y \\ y^2 t_y + x^2 t_x \end{bmatrix} \tag{1} $$

Here $\kappa$ is a geometric factor of order unity which depends on the column design and $L$ is the distance from the exit of the final lens to the wafer. The $x y$ terms give rise to keystone distortion, whereas the $x^2$ and $y^2$ terms lead to pattern placement error but have no effect on stitching.

### 3. Methodology

We coated 25 mm squares of silicon with 300 nm of polymethylmethacrylate and carried out electron beam lithography using a Vistec VB6 UHR EWF tool. This can write 10 nm lines across its 1.2 mm writing field, and the control software makes it easy to apply a small offset to the main field keystone correction. The substrates were developed using 2.5:1 IPA:MIBK at 23 °C and rinsed with IPA. They were deliberately placed in the tool at a range of tilt angles.

The pattern was a single 1.2 mm field and contained 5 verniers on each side, measuring $x$ and $y$ stitch errors to an accuracy of about 1 nm using an optical microscope[5]. The verniers were read by a macro in ImageJ[6] to minimise human bias in the interpretation of the results. The pattern was repeated in a 3 by 3 array on a 1.15 mm pitch so that the verniers overlapped to give stitch measurements. Up to 16 different arrays were written on each substrate and different keystone offsets were applied to the arrays.

### 4. Results and Discussion

#### A. Single Tilt

Figure 2 shows the field distortion in a 1.2 mm field, as deduced from the stitch errors, on a substrate tilted by (-0.2, -2.0) mrad. The errors are as predicted in the geometric model.
described above inasmuch as they are mainly keystone with near zero error in the centre of
the edges. The substrate tilt is almost entirely in the y direction, yet keystone error can
clearly be seen in both the x and the y directions as seen from the longer edges on the left
and bottom. This is in keeping with the rotation expected from the model.

In Fig. 3 we show the effect of adding different keystone corrections to the main field in
both x and y. The substrate tilt in this case was (−1.7, -0.9) mrad. The keystone error in x
was found from

\[
k_x = \frac{(\Delta x_{++} - \Delta x_{--} + \Delta x_{-+} - \Delta x_{+-})}{f^2}
\]

(2)

where \(\Delta x_{++}, \Delta x_{--}, \Delta x_{-+}\) and \(\Delta x_{+-}\) are the distortion errors in x at the four corners of the field,
and \(f\) is the field size. It can be seen that the measured keystone error varies linearly with
the keystone offset applied. It also shows that by applying suitable offsets to both x and y
keystone it is possible to remove the keystone error caused by tilt.

B. Many Tilts

In order to correct for tilt errors we must first establish the relationship between keystone
error and tilt. Equations (1) and (2) predict a linear relationship. Measurements of the
keystone error were carried out for a range of different tilts and these are summarised in
Table I. A least squares fit gave the following relationship between keystone error and tilt
for the VB6 at 100 kV:

\[
\begin{pmatrix}
k_x \\
k_y 
\end{pmatrix} = \begin{pmatrix}
-11.8 t_x + 16.4 t_y \\
18.7 t_x + 10.5 t_y
\end{pmatrix}
\]

(3)

The fitting parameter R was 0.998 and 0.995 for x and y respectively demonstrating a good
fit. The final lens current does not change with beam current so these results will hold for
all beam currents at 100 kV. The difference between the parameters for the x and y
keystone values may arise from the slightly different positions of the x and y scan coils.

C. Tilt Correction

In order to correct for these keystone errors we used the graph shown in fig. 3 which gives
the relationship between keystone error and the applied offset. For different values of tilt
we found the gradient \(\Delta(\text{measured error})/\Delta(\text{offset applied})\) remained constant. Thus to
correct for keystone errors generated by tilt the following procedure was adopted: (a)
measure the tilt of the substrate at the point in question using the VB6 height meter; (b) use
equation (3) to calculate the keystone errors generated; and (c) calculate and apply the
required keystone correction. We carried out tilt measurements by measuring a large array of heights across the substrate prior to exposure and calculating the gradient.

This procedure was applied to a substrate with a (-0.2, -2.0) mrad tilt error and the results are shown in Figure 2. Much lower stitch errors and corresponding scan distortions were measured after the keystone error was applied. There was a reduction from 34 to 12 nm in the maximum stitch error. We also obtained a significant improvement in the maximum stitch error when the tilt was much less, as shown in table I.

For applications requiring absolute position accuracy, for instance when one level is aligned to another, there can still be some tens of nanometres of non-linear gain error which keystone correction does not repair. But using equation (1) it should also be feasible to correct for this if the tool allows the user to specify $x^2$ and $y^2$ correction terms. The VB6 does allow this, but we have not demonstrated that here.

5. Conclusions

We have shown that substantial reductions in stitch errors caused by tilt can be made by applying a suitable keystone correction. For tilts up to 2.5 mrad the stitching can be reduced to values close to that of untilted substrates. This is useful for many applications requiring accurate stitching, for example phase gratings. It is particularly useful in a University environment where many small substrates require to be exposed as it saves a great deal of time in making sure they are level, thus increasing throughput. It is also relevant in situations where only entire wafers are written, as even here tilts of 0.5 mrad are easily possible and substantial reductions in stitch error can be made.

6. Acknowledgements

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7. References


**Figures**

Figure 1; (a) and (b) show the simple model from the side and top respectively; (c) and (d) show the model incorporating rotation through the lens again from the side and the top.

Figure 2. Field distortions as measured from stitch errors; substrate tilt was (-0.2, -2.0) mrad
Figure 3: Keystone error plotted against applied keystone offset; the substrate tilt was (–1.7, -0.9) mrad

![Keystone error vs applied offset](image)

**Tables**

Table 1: Substrate tilts, measured keystone error \(10^{-6}\,\text{mm}^{-1}\) and the predictions from equation (3). The maximum measured stitch error with and without (as is) tilt correction are also shown for three substrates.

<table>
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<th>tilts (mrad)</th>
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<th>model</th>
<th>max stitch error (nm)</th>
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<td>y</td>
<td>x key</td>
<td>y key</td>
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<tr>
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Table 1